Applied Electromagnetics

Outputs

- Analytical models in applied electromagnetics.
- Metamaterials theoretical investigation.

ITS has a rich history of developing theoretical electromagnetic (EM) models for a wide variety of propagation scenarios. Recently, an emphasis has been placed on the EM behavior of complex structures and materials to support innovative designs of sophisticated devices for more versatile radio applications. EM theory is based on solutions to Maxwell's equations. When applied to realistic scenarios with broken symmetries and limiting dimensions, solutions involve complex variables and integrals with no closed-form solution. Although computational methods (e.g., finite-difference time-domain and finite difference) provide means to solve such problems, we focus on analytical techniques to provide intuitive understanding of physical phenomena.

Modeling the EM properties of homogeneous media gives a classic example of analytic modeling. Considering a tangible number of sources, closed-form theoretical solutions are obtainable for the electric and magnetic fields everywhere in space. However, this method is not practical for modeling of the prohibitively large number of sources that occur at the atomic level. Methods involving spatially-averaged or macroscopic field quantities are more relevant. In the presence of applied fields, macroscopic field relations are dependent on average moment densities of the medium and are derived from multipole expansions of the averaged charge and current densities. All multipole moments combine to form classical models for permittivity ($\boldsymbol{D}=\epsilon\boldsymbol{E}$) and permeability ($\boldsymbol{H}=\boldsymbol{B}/\mu$).

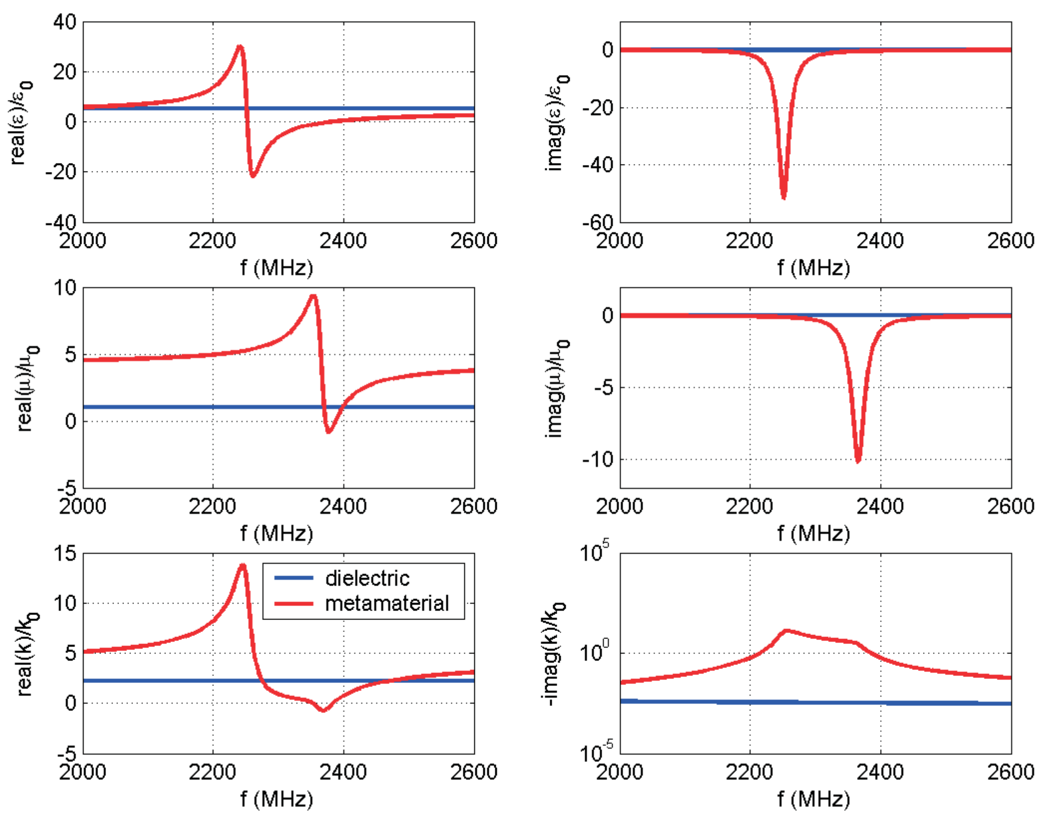

Figure 1. Double-negative material properties of a metamaterial composed of non-conducting spherical particles compared to material properties of a dielectric.

In applied EM scenarios, the scatterers inside man-made structures are typically metal or dielectric objects with dimensions ranging from relatively large to nanometer size. Whether induced moments arise from atomic-size scatterers or from macroscopic aggregates of matter, as long as wavelength is substantially larger than the dimensions and spacings of scatterers, the concept of effective medium parameters remains valid. Similarly, quasi-static approximations at relatively large wavelengths provide means to model complex structures and geometries into effective properties. For example, complicated 2d arrays and thin layers can be modeled with equivalent impedance surfaces, periodic arrays of conducting wires or small metal particles can be modeled with a sheet of average current, and arrays or random mixtures of particles in 3d can be modeled with effective medium parameters.

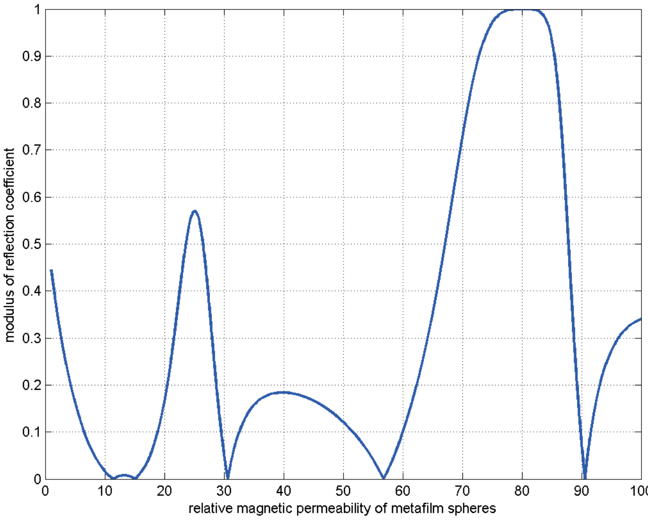

Figure 2. Metafilm reflection coefficient modulus versus magnetic permeability of spherical particles inside metafilm.

When wavelengths are comparable to and smaller than the dimensions and spacings of the scatterers, fields no longer see the composite as an effective media and more elaborate techniques to analyze the EM field interaction are necessary. Some interesting highly-dispersive EM behavior occurs. For periodic composite materials, resonances occur due to the size of the scatterer. At wavelengths near resonance, the electric and magnetic polarizations associated with individual inclusions can be simultaneously 180° out of phase with the applied **E** and **H** fields; the consequent phase velocity is in the opposite direction of the energy flow of the propagating wave in order to uphold the radiation condition. This scenario is equivalent to simultaneously negative real parts of $\in$ and μ (see Figure 1 on previous page). Materials of this type have not been found in nature and have been referred to as double-negative, negative-index, and left-handed materials. They have received a great deal of attention because of their great potential for new applications.

Metamaterials are engineered composites that are designed to take advantage of such properties. These types of man-made materials are commonly engineered by designing specifically shaped scatterers embedded periodically through a volume in order to achieve a desirable bulk effect. Obviously, the more control we have over the properties of the metamaterial, the more applications we can get out of it. In fact, it has been shown that a metafilm composed of magneto-dielectric spherical particles can be designed to have total transmission or total reflection (see Figure 2 above). Further, if the inclusions were made from a material wherein its properties could be changed in real-time (e.g., with a biasing field or voltage), then a controllable surface can be realized. It is not too hard to imagine adaptable antennas and radomes that control the direction of emission, enhance emission rate, suppress interference, and perform other types of system optimization.

In our efforts we have conducted comprehensive and mathematically rigorous analyses of fundamental electromagnetic concepts applied to metamaterials. Topics include modeling the electric and magnetic polarization of metamaterials, deriving the propagation characteristics for various fundamental geometries, and exploring limitations imposed by finite dimensions of the bulk composite. Investigation into electronically controlling the electric and magnetic properties of metamaterials will also be a subject for study in pursuit of adaptable applications.

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